ARKIV FÖR FYSIK Band 19 nr 30

Communicated 8 February 1961 by The Svedberg and Arne Westgren

Nuclear spectroscopy on $_{81}Tl^{197}$ sources

By B. Jung and J. Svedberg

With 3 figures in the text

ABSTRACT

The conversion electron spectrum of mass-separated Tl^{197} sources was studied from 5 to 2000 keV in a double focusing β-spectrometer, adjusted to a momentum resolution of about 0.5 %. Energy sum and intensity relations between the γ-transitions indicate the following level sequence in $_{80}Hg^{197}$: ground state (1/2 –), 133.95 (5/2 –), 152.15 (3/2 –), 308.5 (3/2 –), 578.1 (1/2 –) and 585.6 keV (3/2 –). The level scheme was partially checked by measurements of $e^- - \gamma$ coincidences. The half-life of Tl^{197} was found to be 2.84 ± 0.04 h. Conversion electron lines in the decay of the daughter nucleus Hg^{197} (65 h) were studied to some extent.

1. Introduction

In the present study we pursue the work on the decays of neutron-deficient odd-mass thallium isotopes, which was initiated recently with a study of the decay of Tl^{199} [1]. The work is justified on account of our poor knowledge of these decays, especially those of the lower mass isotopes, and by their bearing on the systematics of nuclei differing by two neutrons. The systematics has been rather successful in this mass region [2, 3], but the level sequences in Hg^{201} and Hg^{199} are difficult to correlate, Hg^{201} having the sequence, ground state (3/2 –), 1.6 (1/2 – or 5/2 –), 32 (1/2 – or 3/2 –) and 167 keV (1/2 – or 3/2 –) [4] and Hg^{199} the sequence, ground state (1/2 –), 158 (5/2 –), 208 (3/2 –), 403 (1/2 –), 455 (1/2 –) and 492 keV (3/2 –) [1]. It is hoped that information on the lower odd-mass mercury isotopes will contribute to a better understanding of the sudden change. The decay of Tl^{195} is now being studied with similar techniques as earlier Tl^{199} [1] and in this work Tl^{197}.

The decay of Tl^{197} has been studied by Knight and Baker [5] and by Andersson *et al.* [6]. (The discovery of Tl^{197} was first announced in a preliminary report [7] of the latter work). From measurements of the conversion electron spectra of mass separated sources, Andersson *et al.* [6] ascribed three γ-transitions (133.5, 151.7 and 173.1 keV) to the decay. A fourth γ-transition (426 keV) was reported in a later work [8]. An energetically coinciding transition in the decay of Tl^{196} prevented its detection in the earlier study.

2. Experimental procedures

The thallium activities were produced in the Werner synchrocyclotron by bombardments of natural mercurous chloride with protons of 75 MeV maximal energy for 3 h. After standard chemical separations [9] the activities were fed (in the form of TlCl) to the ion source of the mass separator [10, 11]. The Tl^{197+} ion current was collected directly on 2 mg/cm^2 aluminium foils. The mass-separated sources, having approximate dimensions of 1.5×25 mm, were measured in a double focusing β-spectrometer [12]. Conversion electrons of energies lower than 540 keV were studied with a momentum resolution of 0.5 % and the energy range 540 to 700 keV with a momentum resolution of 0.4 %. Increased transmission was needed for conversion electrons of still higher energies, resulting in a reduced momentum resolution (0.6 %). A counter window of about 0.05 mg/cm^2 VYNS (cut-off energy 5 keV) was used in the measurements below 540 keV and a window of 0.9 mg/cm^2 Mylar for higher energies. The energy limits are not strict and in several cases a line was studied under different conditions. The new automatic operation [13] of the spectrometer was used extensively. Each source was measured three times in order to follow the decay of the lines.

The energy calibration of the conversion electron spectrum was made against ThB lines (ThA, ThB, ThF, ThI and ThL, the notation and momentum values taken from Siegbahn and Gerholm [14]) and Tl^{198} lines (K 411.78 keV and K 675.75 keV [15, 16, 17]), following the procedure outlined by Arbman [18]. Composite sources were used, containing ThB + Tl^{197} and Tl^{198} + Tl^{197}. Both sources were prepared in the mass separator, the former by collection of Tl^{197} on an aluminium strip, activated in a ThB source, the latter by intermittent collection of Tl^{198} and Tl^{197}.

The intensities of the conversion lines were obtained by numerical integration of the areas of the lines, the automatic operation of the spectrometer giving data which are easily handled in this way. Allowance was made for decay of the lines and the momentum dependence of the peak areas. The absorption of the electrons in the counter window was corrected for according to the diagram of Saxon [19]. A number of sources were needed before the whole energy range (5 to 2000 keV) was covered and the K and L conversion lines of the 152 keV transition (cf. Table 1) were used to normalize the source intensities. For this reason at least one of them was recorded from each source. Conversion lines in the decay of Hg^{197} were measured on aged sources in order to avoid corrections for the growing-in of this nuclide.

For studies of e^{-}–γ coincidences the β-spectrometer was used in connection with a single-channel γ-spectrometer. The electrons were detected in the ordinary Geiger-Müller counter, the pulses from which were amplified and fed to a coincidence unit. The γ-rays were detected in a $1'' \times 1''$ NaI(Tl) crystal, which was situated between the pole pieces of the spectrometer at a distance of 3 cm from the source. A 50 cm long Perspex light-guide coupled the crystal to an EMI 6097 B photomultiplier, outside the spectrometer magnetic field. The pulses from the photomultiplier were amplified and fed to a single-channel pulse-height analyzer, the output of which was connected to the coincidence unit. An energy resolution of about 15 % was achieved for the 662 keV γ-transition in the decay of Cs^{137}. Almost 100 % coincidence efficiency was found for a coincidence resolving time of 0.2 μs, yielding a prompt resolution curve with a full width at half maximum of 0.4 μs. Lower resolving times caused, however, a reduced efficiency, possibly due to time lag spreads in the Geiger-Müller counter or the pulse-height analyzer. The geometry of the coincidence set-up was such that electrons and γ-rays emitted at right angles to each other were detected.

In the measurements the γ-spectrum in coincidence with a conversion electron line, focused in the β-spectrometer, was scanned with the single-channel analyzer. Only pronounced coincidence effects could be observed because of the short half-life of Tl^{197}, the rather low transmission of the β-spectrometer (with the present slit system about 2 % at most, yielding a momentum resolution of 1 %), and the low photopeak detection efficiency of the 1″ × 1″ crystal.

3. Results and discussion

3.1. Conversion electron spectrum

Owing to incomplete mass separation the Tl^{197} sources also contained impurities of the adjacent masses. (For a discussion of purities of samples in this mass region, prepared with the Werner Institute mass separator, we refer to an earlier paper [17].) Since the half-lives of the major impurities Tl^{196} (1.8 h), Tl^{196m} (1.4 h), Tl^{198} (5.3 h) and Tl^{198m} (1.9 h) are rather close to that of Tl^{197} and the conversion electron spectra of these nuclides have not been studied in detail, the interpretation of the conversion electron spectra of the Tl^{197} sources had to be made with some caution. However, conversion electron spectra of mass separated $Tl^{196} + Tl^{196m}$ and $Tl^{198} + Tl^{198m}$ sources, recorded in another investigation [3], facilitated the mass assignment of the lines considerably. Although these spectra are largely uninterpreted (only some details have been published), comparison of relative intensities of lines recorded from different sources allows in many cases rather firm mass assignments. Table 1 contains the lines, which were established mainly from comparisons of this kind as due to γ-transitions in the decay of Tl^{197}. In several cases the mass assignments are supported also by the measured half-lives. The conversion shell assignments are based on the relative intensities of the lines and the empirical thumb-rules $L/M \approx 3$ and $M/N \approx 3$, from which conversion in the L, M or N shells can often be excluded by the absence of corresponding lines of appropriate intensities, converted in the other shells. Of course, energy differences between the lines were also taken into account. The multipole orders of the transitions were obtained by comparison of the experimental conversion ratios with theoretical ones, calculated from the tables of Rose [20] and Sliv and Band [21].

The following remarks apply to the transitions given in Table 1.

18 keV. The mass assignment of the M line is based on the half-life, since the conversion electron spectra of the adjacent nuclides have not been studied in this low energy region. The given assignment is in accordance with the observation that the relative intensity of the line was the same within 15 % when recorded from two different sources. A different admixture of impurities in the two sources, which might well be expected, should cause different relative intensities, if the line were due to an impurity. The conversion shell assignment follows from the energy difference of the M and N lines. An indication of a line, which might be the M_{II} conversion line was also observed. Apart from this, only three lines were found between 14 and 27 keV and that two of these should have, within close limits, the correct energy difference for M_I and N_I conversion lines of the same transition merely by chance, must be considered highly improbable. $M1$ multipolarity is concluded from the high M_I/M_{II} and M_I/M_{III} ratios.

Table 1. Internal conversion lines in the decay of Tl^{197}.

Conversion ratios within parentheses are interpolated from Rose [20] and Sliv and Band [21]. Mean values are given where the two theoretical calculations differ. The transitions are commented on in the text.

Adopted energy (keV) and multipole order	Conv. shell	Electron energy (keV)	Rel. electron intensity	Half-life (h)	Conversion ratios
18.18 ± 0.03	M_I	14.62 ± 0.03	1.7 ± 0.4	3.0 ± 0.3	$M_I/M_{II} \geqslant 6$
$M1$	N_I	17.41 ± 0.04	0.6 ± 0.2		$M_I/M_{III} \geqslant 10$
					$M_I/N_I = 2.8 \pm 1.2$
133.94 ± 0.05	K	50.83 ± 0.05	4.1 ± 0.8	2.7 ± 0.4	$K/L = 0.35 \pm 0.10$ (0.42)
$E2$	L_{II}	119.73 ± 0.13	7.1 ± 0.4	2.6 ± 0.1	$L_{I+II}/L_{III} = 1.5 \pm 0.1$ (1.48)
	L_{III}	121.69 ± 0.13	4.8 ± 0.3	2.6 ± 0.1	$L/M = 3.8 \pm 0.4$
	M	130.8 ± 0.3	3.1 ± 0.2	2.8 ± 0.1	$M/N+O = 2.6 \pm 0.4$
152.17 ± 0.06	K	69.06 ± 0.06	100	2.8^a	$K/L = 5.9 \pm 0.2$ (6.1)
$M1$	L_I	137.33 ± 0.14	16.6 ± 0.9	2.8^a	$L_{I+II}/L_{III} = 70 \pm 16$ (122)
$(+ \leqslant 2\,\%\ E2)$	L_{III}	139.9 ± 0.5	0.25 ± 0.04		$L/M = 4.3 \pm 0.3$
	M_I	148.6 ± 0.4	3.8 ± 0.3	2.7 ± 0.1	
156.3 ± 0.3	K	73.2 ± 0.3	1.1 ± 0.1		$K/L = 4 \pm 2$ (6.1)
$M1$					
173.8 ± 0.3	K	90.7 ± 0.3	2.3 ± 0.2		$K/L = 6 \pm 2$ (6.1)
$M1$	L_I	159.2 ± 0.6	0.4 ± 0.1		
269.6 ± 0.2	K	186.5 ± 0.2	1.7 ± 0.1	2.9 ± 0.1	$K/L \geqslant 4.4$
$M1$					
277.5 ± 0.5	K	194.4 ± 0.7	0.9 ± 0.2	2.8 ± 0.4	$K/L \geqslant 5$
$M1$					
308.5 ± 0.2	K	225.3 ± 0.2	5.3 ± 0.3	2.8^a	$K/L = 4.2 \pm 0.9$
$(50 \pm 25)\,\%$					
$M1 +$	L_I	293.7 ± 0.3	1.3 ± 0.2	3.0 ± 0.4	$L_{I+II}/L_{III} \approx 7$
$(50 \pm 25)\,\%$					
$E2$	M_I	304.9 ± 1.4	0.4 ± 0.1		$L/M = 3.0 \pm 0.6$
426.0 ± 0.3	K	342.9 ± 0.3	9.5 ± 0.5	3.1 ± 0.4	$K/L = 6.0 \pm 0.7$ (6.1)
$M1$	L_I	411.2 ± 1.2	1.6 ± 0.2	2.7 ± 0.2	$L/M = 3.0 \pm 1.7$
	M_I	422.5 ± 1.5	0.6 ± 0.2		
433.1 ± 0.4	K	350.0 ± 0.4	1.9 ± 0.1	3.0 ± 0.2	$K/L = 9 \pm 3$ (6.1)
$M1$	L_I	418.9 ± 1.5	0.2 ± 0.1		$L/M = 4 \pm 3$
	M_I	430 ± 2	0.08 ± 0.04		
443.6 ± 1.7	K	360.4 ± 1.7	0.14 ± 0.04		
451.8 ± 0.4	K	368.7 ± 0.4	0.35 ± 0.08	3.1 ± 0.7	$K/L > 4$
$M1$					
578.3 ± 0.5	K	495.2 ± 0.5	1.3 ± 0.2	2.7 ± 0.7	$K/L = 7 \pm 3$
$M1$	L	564.2 ± 1.7	0.18 ± 0.07		
585.3 ± 1.7	K	502.2 ± 1.7	0.3 ± 0.1		
791 ± 5	K	708 ± 5	0.15 ± 0.03	2.7 ± 0.5	
857 ± 5	K	773 ± 5	0.25 ± 0.05	2.8 ± 0.5	
	L	841 ± 7	0.02 ± 0.01		
892 ± 7	K	809 ± 7	0.12 ± 0.03	2.7 ± 0.8	
983 ± 6	K	900 ± 6	0.15 ± 0.03	3.2 ± 0.7	
1010 ± 6	K	927 ± 6	0.12 ± 0.03	2.7 ± 0.7	

[a] Cf. sub-section 3.2.

Table 2. Uninterpreted lines.

In cases where comparison with Tl^{196} + Tl^{196m} and Tl^{198} + Tl^{198m} spectra indicates or excludes one of these masses, this is remarked in the third column without differentiating between ground and isomeric states.

Electron energy (keV)	Half-life (h)	Remarks
22.3	< 8	
72.3	3	Not resolved from L_{III} 84 (Tl^{196})
111.8	< 4	
143.4	2.5	Tl^{198} ?, not Tl^{196}
166.4	≈ 3	
188.9	< 4	Tl^{198} ?
191.1	1.8	Tl^{198} ?
202.3		
204.6	< 3	
211.6	< 2	Tl^{198} ?
218	< 4	
554	2.3	Tl^{196} ? Tl^{198} ?
558	4	Tl^{196} ? Tl^{198} ?
593	20	Tl^{198} ?
596		Tl^{198} ?

134 keV. As pointed out by Andersson *et al.* [6] this transition is most probably identical with the 134 keV $E2$ transition found in the decay by internal transition of Hg^{197m} (24 h). Both the transition energy and the conversion ratios support this conclusion, the energies and conversion ratios reported in the decay of Hg^{197m} being: 133 keV, $K/L = 0.4$ [22], 134.3 keV, $K/L < 0.1$ [23], 134.0 keV, $L_I/L_{II}/L_{III} = 0.04/1.1/1$ [24] and $K/L = 0.46 \pm 0.02$, $L_I/L_{II}/L_{III} = 0.26 \pm 0.03/1.45 \pm 0.09/1.00 \pm 0.05$ [25].

152 keV. The L_{I+II}/L_{III} ratio is lower than predicted by theory [20, 21] for a pure $M1$ transition, which may indicate an $E2$ admixture of up to 2 %. The line interpreted as L_{III} may, however, partially be due to Tl^{196} impurity.

156 keV. The K line is not completely resolved from the growing-in M 77 keV complex in the decay of Hg^{197} (65 h) [23, 24, 26] which explains why only an upper half-life limit is given. Interpreting a weak bump in the spectrum as the corresponding L line, one finds a K/L ratio of 4 ± 2. $M1$ multipolarity is assumed since $E2$ would give a K/L ratio of 0.6, but appreciable $E2$ admixture is not excluded.

270 keV. This transition is probably identical with the 269 keV transition, tentatively ascribed to Tl^{197} by Andersson *et al.* [6].

309 keV. The K/L ratio indicates 50 % $M1$ + 50 % $E2$, which is also compatible with the L_{I+II}/L_{III} ratio.

426 keV. Although Tl^{196} + Tl^{196m}, which was certainly present in our sources as an impurity, has an energetically coinciding transition [8] it can be concluded from a

Table 3. Lines interpreted as due to impurities.

Electron energy (keV)	Half-life (h)	Interpretation
33.1		L_{I} 48 Tl^{198m}
33.7	1.7	L_{II} 48 Tl^{198m}
35.6	1.6	L_{III} 48 Tl^{198m}
44.6	<2.4	M_{II} 48 Tl^{198m}
45.0	<2.4	M_{III} 48 Tl^{198m}
47		N 48 Tl^{198m}
48		O 48 Tl^{198m}
70.0	1.5	$L_{\mathrm{I+II}}$ 84 Tl^{196m}
71.9	1.3	L_{III} 84 Tl^{196m}
81.3	1.7	M 84 Tl^{196m}
83.8		N 84 Tl^{196m}
125.1	8	K 208 Tl^{199}[a]
164.3	7	K 247 Tl^{199}[a]
175.6	1.8	K 261 Tl^{198m}
197.4	1.9	K 282 Tl^{198m}
245.7	1.9	$L_{\mathrm{I+II}}$ 261 Tl^{198m}
248.4	1.8	L_{III} 261 Tl^{198m}
257.7	<2	M 261 Tl^{198m}
260.5	1.9	N 261 Tl^{198m}
267.7	1.5	L 282 Tl^{198m}
280	1.8	M 282 Tl^{198m}
329	3.4	K 412 Tl^{198}
1115		K 1198 Tl^{198}

[a] The presence of these two Tl^{199} lines may be explained by an accident during the mass separation, since they were measured from the same source.

comparison with a Tl^{196} + Tl^{196m} conversion electron spectrum, that at most 5 % of the intensity of the K line was due to Tl^{196} + Tl^{196m} impurity in the source.

Table 2 contains lines for which neither the mass assignment nor the conversion shell could be established with certainty. Comparison with Tl^{196} and Tl^{198} spectra revealed, however, in some cases an indication as to the mass assignment, which has been noted in the remarks column. All the lines were barely detectable, which corresponds to an intensity less than 1 % of the K 152 keV conversion line (cf. Table 1).

Lines interpreted from refs. 1, 3, 5 and 17 as due to impurities are collected in Table 3. The two lines ascribed to Tl^{199} were recorded from the same source and the unexpected presence of detectable amounts of this nuclide can thus be explained by an isolated accident during the mass separation of that source. It should be pointed out that these lines are the two strongest ones in the conversion electron spectrum of Tl^{199} [1].

The energies of the two transitions in the decay of Hg^{197} (65 h), which are given in Table 4, are in good agreement with earlier reported values: 77.6 and 191.4 keV [23], 77.4 and 191.6 keV [24], 77.6 and 191.8 keV [26] and 77.4 and 191.2 keV [27]. The last pair of values was measured in the decay of Pt^{197} (20 h). van Heerden *et al.* [25] report 77.51 ± 0.03 keV, which is not in full agreement with our value. They based, however, their energy calibration on the energy values 134.0 and 165.3 keV [24] for the transitions in the decay by internal transitions of Hg^{197m} (24 h), and the

Table 4. Conversion lines in the decay of Hg^{197} (65 h).

Adopted transition energy (keV) and multipole order	Conv. shell (Au)	Electron energy (keV)	Relative electron intensity (L_I 77 = 100)	Conversion ratios
77.31 ± 0.14 (89 ± 2) % $M1 + (11 \pm 2)$ % $E2$	L_I	62.96 ± 0.14	100	$L_I/L_{II}/L_{III} =$ $= 100/44 \pm 3/41 \pm 3$
	L_{II}	63.58 ± 0.16	44 ± 3	$L/M = 3.6 \pm 0.5$
	L_{III}	65.4 ± 0.2	41 ± 3	$M/N = 3.5 \pm 0.8$
	M	74.1 ± 0.2	51 ± 5	
	N	76.8 ± 0.2	15 ± 2	
191.5 ± 0.2	K	110.82 ± 0.17	1.6 ± 0.2	

disagreement is, therefore, not considered significant. The L subshell ratios of the 77 keV transition were measured in a special run with improved resolution (0.29 %). They compare well with earlier reported $L_I/L_{II}/L_{III}$ ratios: 100/45/34 [24], 100/46/34 [26] and $3.06 \pm 0.13/1.35 \pm 0.07/1.00 \pm 0.04 = 100/44 \pm 4/33 \pm 3$ [25]. Comparison with the theoretical subshell conversion ratios given by Rose [20] and by Sliv and Band [21] shows that the measured ratios are compatible only with a mixed $M1 + E2$ transition ((90 ± 1) % $M1$ can be calculated from the L_I/L_{II} ratio and (88 ± 1) % $M1$ from the L_I/L_{III} ratio) or an $E1$ transition (the theoretical $L_I/L_{II}/L_{III}$ ratio being 100/46/52 [20, 21]). The latter possibility is, however, ruled out by the measured total conversion coefficient $\alpha = 2.3$ [26]. The L 77/K 192 intensity ratio $185/1.6 = 116$ is in nice agreement with the measurement by Joly *et al.* [26], who found an L 77/K 192 ratio of $831/7.15 = 116$.

The Auger spectra of neutron-deficient thallium nuclides were discussed to some extent in connection with the study of the decay of Tl^{199} [1] and will not be specially treated here, mainly because of the interference caused by the growing-in mercury activity. Comparison of the spectra recorded in the two studies reveals that no strong Tl^{197} conversion line is situated either in the K- or in the L-Auger complex.

3.2. *Half-life of* Tl^{197}

The decays of some prominent Tl^{197} conversion lines were followed by the automatic count registration and print-out equipment. The lines were focused in the β-spectrometer and the magnet current kept constant. Least squares analyses of the decay curves yielded the following half-lives, in which the errors are purely statistical: 2.81 ± 0.03, 2.823 ± 0.007 and 2.876 ± 0.011 h (K 152 keV), 2.869 ± 0.009 h (L 152 keV) and 2.83 ± 0.02 h (K 309 keV). In order to allow for the systematical errors, which are evident from these values, we give the half-life of Tl^{197} as 2.84 ± 0.04 h. This value compares well with earlier reported 2.8 ± 0.2 h [5] and 2.7 ± 0.2 h [6].

3.3. *γ-spectra in coincidence with conversion electron lines*

The coincidence studies were limited for intensity reasons to the γ-spectra in coincidence with the strong conversion lines K 152, K 309 and K 426 keV (cf. Table 1). Two of the spectra obtained in these studies are given in Fig. 1 and Fig. 2. For com-

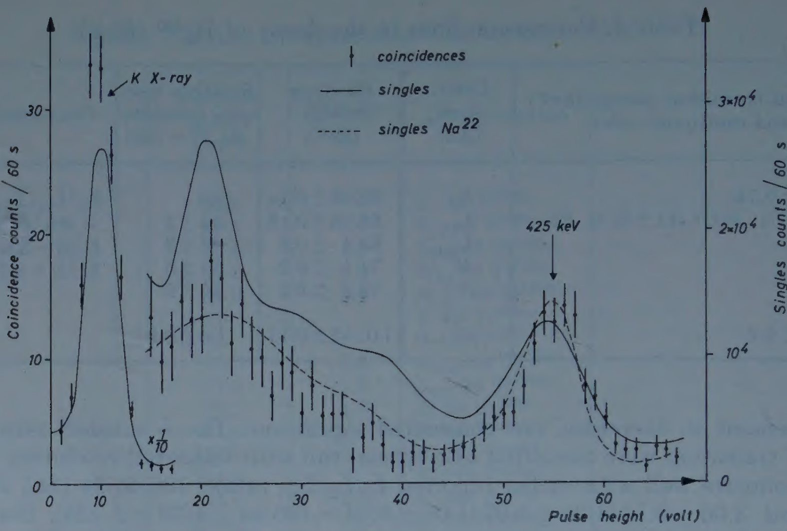

Fig. 1. γ-spectrum in coincidence with K conversion electrons of the 152 keV transition. The Na^{22} singles spectrum, incorporated to allow a comparison of the Compton distributions, was recorded with reduced amplification to get the 511 keV annihilation peak falling on the 425 keV coincidence peak, to which it was also normalized in intensity.

parison the singles spectra are incorporated in the figures. Corrections for decay of the samples and for the almost negligible chance coincidence effect were applied. The decay corrections of the singles spectra are, however, not accurate, since no allowance was made for impurities in the samples. The coincidence counting rates were rather low and the measurements had to be extended over more than one half-life of the

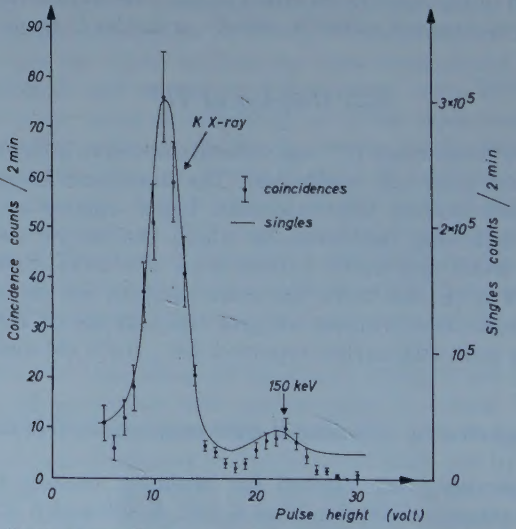

Fig. 2. γ-spectrum in coincidence with K conversion electrons of the 426 keV transition.

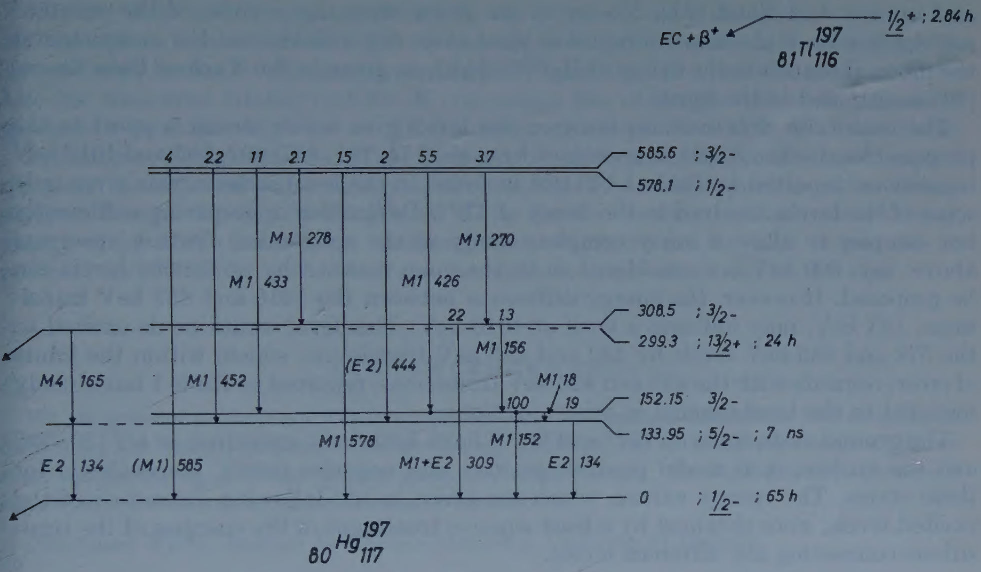

Fig. 3. Proposed level scheme of Hg^{197}. All energies are given in keV and the total transition intensities, normalized to the intensity of the 152 keV transition, are indicated at the tails of the transition arrows.

Tl^{197} sources. The peak at about 70 keV, prominent in both coincidence spectra, is interpreted as due to *K* X-rays. Strong coincidence effects with these must be expected in both cases. The peak at about 425 keV in Fig. 1 is probably caused by the 426 keV transition, but at least part of the peak may be due to the 433 keV transition (cf. Table 1). The coincidence relation between the 426 and the 152 keV transitions is more firmly established in Fig. 2, where the energy of the coincidence peak at 150 keV is too high to be explained by only the 134 keV transition (cf. Table 1). The coincidence effect found in the region between the 70 and 425 keV peaks in Fig. 1 can be explained by the Compton distribution of the 425 keV line, as can be seen by comparison with the Na^{22} singles spectrum given in the figure.

The γ-spectrum in coincidence with *K* 152 keV conversion electrons was studied also at higher energies. A positive coincidence effect was found up to at least 1 MeV, but little structure was revealed above about 425 keV, which might be explained by very poor counting statistics (about 3 coincidence counts per minute). The γ-spectrum in coincidence with the *K* 309 keV conversion line showed no structure above the *K* X-ray peak, but a positive coincidence effect was found up to at least 350 keV.

3.4. *Level scheme of Hg^{197}*

The coincidence information reported in sub-section 3.3 and energy sum relations between the transitions listed in Table 1 form the basis for the level scheme presented in Fig. 3. The figures at the tails of the transition arrows indicate the total transition intensities, relative to the 152 keV transition, and were calculated from the conversion line intensities with the theoretical conversion coefficients given by Rose [20] and by Sliv and Band [21]. No errors are given since the purities of the assumed multipolarities of the transitions are in most cases not well-known. For completeness the internal branch in the decay of Hg^{197m} (24 h), as given in the Nuclear Data Sheets [28], is included in the figure.

The multitude of transitions between the levels give rather strong support to the proposed level scheme, but as is evident from the 174, 791, 857, 892, 983 and 1010 keV transitions, reported in Table 1 but not included in the level scheme, this gives only some of the levels involved in the decay of Tl^{197}. Difficulties in preparing sufficiently hot samples to allow a fairly complete study of the conversion electron spectrum above, say, 600 keV are considered to be the main reason why no further levels can be proposed. However, the energy difference between the 1010 and 857 keV transitions, 153 keV, may indicate a level at 1010 keV. This level would be de-excited to the 578 and 585 keV levels by 432 and 425 keV transitions, which, within the limits of error, coincide with the 433 and 426 keV transitions, reported in Table 1 but already included in the level scheme in other positions.

The ground state spins of Tl^{197} and Hg^{197} have both been measured as 1/2 [29, 30], and the nuclear shell model predicts positive and negative parity, respectively, for these states. The energy values, which are given in the following discussion of the excited levels, were obtained by a least squares treatment of the energies of the transitions connecting the different levels.

133.95 ± 0.04 keV. A spin-parity of 5/2 − is evident from the $E2$ character of the de-exciting transition. The half-life of the level has been measured as 7 ± 1 [31] and 8 ns [32] in the decay of Hg^{197m} (24 h). When these measurements were performed, the 134 keV transition was, however, believed to be emitted in Au^{197}.

152.15 ± 0.04 keV. For intensity reasons the 152 keV transition evidently goes to the ground state. A spin-parity of 3/2 − follows from the $M1$ character of the de-exciting transitions. No relative total intensity is given for the 18 keV transition, since the L-conversion lines were not detected, and the L/M ratio and the L conversion coefficients are not known at this low energy.

308.49 ± 0.16 keV. Spin-parity 3/2 − follows from the mixed $M1 + E2$ character of the transition to the 1/2 − ground state. The transition to the 134 keV (5/2 −) level may be masked by the 173.8 keV transition (cf. Table 1) and has, if $M1$, an upper total intensity limit of 1.3 % of the 152 keV transition. The energy of the 173.8 keV transition was measured several times and was found to be incompatible with the energy difference between the 308 and 134 keV levels.

578.13 ± 0.19 keV. If not a ground state transition, the 426 keV transition can, for intensity reasons, only be followed by the 152 keV transition. The coincidence relation between the 152 and 426 keV transitions, reported in subsection 3.3, excludes the former possibility. A spin-parity of 1/2 − is proposed from the weakness of the transition to the 134 keV (5/2 −) level. An $E2$ multipole character was assumed for this transition, when the total transition intensity was calculated. The weakness of the 270 keV transition explains why no coincidence relation between this and the 309 keV transition could be established in the coincidence measurements (cf. subsection 3.3).

585.62 ± 0.25 keV. A spin-parity of 3/2 − is proposed, since the level de-excites by $M1$ transitions to the 152 keV (3/2 −) and 134 keV (5/2 −) levels and since 5/2 − is less probable as the level is rather strongly fed from the 1/2 + ground state of Tl^{197}. Also the measured intensity of the K conversion line of the ground-state transition appears to be rather high for an $E2$ transition in competition with $M1$ transitions.

Preliminary measurements [33] of the positron spectrum of Tl^{197} indicate a complex spectrum with an end-point energy of about 1.2 MeV. As one expects a rather strong positron branch directly to the ground state, the results may indicate a total decay energy of 2.2 MeV. Coincidence measurements, which we are not able to perform at present, are, however, needed before more definite conclusions can be drawn.

ACKNOWLEDGEMENTS

We are grateful to Professor The Svedberg for excellent working conditions. The cooperation of fil. mag. I. B. Häller, fil. kand. T. Stenström, ing. R. Ringh, Mr. H.-G. Rikner and the cyclotron staff, headed by ing. Å. Svanheden, is thankfully acknowledged. The work has been financially supported by the Swedish Atomic Research Council.

The Gustaf Werner Institute for Nuclear Chemistry, University of Uppsala.

REFERENCES

1. Jung, B., and Svedberg, J., Nuclear Phys. *20*, 630 (1960).
2. Bergström, I., and Andersson, G., Arkiv Fysik *12*, 415 (1957).
3. Jung, B., and Andersson, G., Nuclear Phys. *15*, 108 (1960).
4. Herrlander, C. J., Stockendal, R., and Gupta, R. K., Arkiv Fysik *17*, 315 (1960).
5. Knight, J. D., and Baker, E. W., Phys. Rev. *100*, 1334 (1955).
6. Andersson, G., Arbman, E., and Jung, B., Arkiv Fysik *11*, 297 (1957).
7. Andersson, G., Arbman, E., Bergström, I., and Wapstra, A. H., Phil. Mag. *46*, 70 (1955).
8. Andersson, G., Burgman, J. O., and Jung, B., Phil. Mag. *3*, 105 (1958).
9. Andersson, G., and Bergström, I., Nuclear Phys. *3*, 506 (1957).
10. Andersson, G., Arkiv Fysik *12*, 331 (1957).
11. Burgman, J. O., and Andersson, G., Nucl. Instr. *3*, 33 (1958).
12. Arbman, E., and Svartholm, N., Arkiv Fysik *10*, 1 (1955).
13. Arbman, E., and Jung, B., Nucl. Instr. & Meth. *10*, 322 (1961).
14. Siegbahn, K., and Gerholm, T. R., Appendix 7 of Beta- and Gamma-Ray Spectroscopy (Ed. Siegbahn, K.), North-Holland Publishing Co., 1955.
15. Vries, C. de, and Dijkstra, J. H., Nuclear Phys. *18*, 446 (1960).
16. Bäckström, G., and Bergman, O., Arkiv Fysik *13*, 393 (1958).
17. Jung, B., Nuclear Phys. *10*, 440 (1959).
18. Arbman, E., Dissertation, Uppsala (1958).
19. Saxon, D., Phys. Rev. *81*, 639 (1951).
20. Rose, M. E., Internal Conversion Coefficients, North-Holland Publishing Co., 1958.
21. Sliv, L. A., and Band, I. M., Tables of Internal Conversion Coefficients of Gamma Rays, Academy of Sciences Press (U.S.S.R.), 1956, 1958.
22. Huber, O., Humbel, F., Schneider, H., de-Shalit, A., and Zünti, W., Helv. Phys. Acta *24*, 127 (1951).
23. Cork, J. M., Martin, D. W., LeBlanc, J. M., and Branyan, C. E., Phys. Rev. *85*, 386 (1952).
24. Mihelich, J. W., and de-Shalit, A., Phys. Rev. *91*, 78 (1953).
25. Heerden, I. J. van, Reitmann, D., and Schneider, H., Nuovo cimento *11*, 167 (1959).
26. Joly, R., Brunner, J., Halter, J., and Huber, O., Helv. Phys. Acta *28*, 403 (1955).
27. Cork, J. M., LeBlanc, J. M., Stumpf, F. B., and Nester, W. H., Phys. Rev. *86*, 415 (1952).
28. Nuclear Data Sheets, National Academy of Sciences — National Research Council (Washington, D.C., 1958).

29. Brink, G. O., Hubbs, J. C., Nierenberg, W. A., and Worcester, J. L., Phys. Rev. *107*, 189 (1957).
30. Melissinos, A. C., Phys. Rev. *115*, 126 (1959).
Mellissinos, A. C., and Davis, S. P., Phys. Rev. *115*, 130 (1959).
31. McGowan, F. K., Phys. Rev. *77*, 138 (1950), *78*, 325A (1950).
32. Deutsch, M., and Wright, W. E., Phys. Rev. *77*, 139 (1950).
33. Jung, B., and Andersson, G., Unpublished work.

Tryckt den 20 april 1961

Uppsala 1961. Almqvist & Wiksells Boktryckeri AB